Towards Efficient Electric Vehicle Charging Using VANET-Based Information Dissemination

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Abstract—The design of an efficient charging management system for on-the-move Electric Vehicles (EVs) has become an emerging research problem, in future connected vehicle applications given their mobility uncertainties. Major technical challenges here involve decision-making intelligence for the selection of Charging Stations (CSs), as well as the corresponding communication infrastructure for necessary information dissemination between the power grid and mobile EVs. In this article, we propose a holistic solution that aims to create high impact on the improvement of end users' driving experiences (e.g., to minimize EVs' charging waiting time during their journeys) and charging efficiency at the power grid side. Particularly, the CS-selection decision on where to charge is made by individual EVs for privacy and scalability benefits. The communication framework is based on a mobile Publish/Subscribe (P/S) paradigm to efficiently disseminate CSs condition information to EVs on-the-move. In order to circumvent the rigidity of having stationary Road Side Units (RSUs) for information dissemination, we promote the concept of Mobility as a Service (MaaS) by exploiting the mobility of public transportation vehicles (e.g. buses) to bridge the information flow to EVs, given their opportunistic encounters. We analyze various factors affecting the possibility for EVs to access CSs information via opportunistic Vehicle-to-Vehicle (V2V) communications, and also demonstrate the advantage of introducing buses as mobile intermediaries for information dissemination, based on a common EV charging management system under the Helsinki city scenario. We further study the feasibility and benefit of enabling EVs to send their charging reservations involved for CS-selection logic, via opportunistically encountered buses as well. Results show this advanced management system improves both performances at CS and EV sides.

Index Terms—Electric Vehicle Charging, Wireless Communication, Publish/Subscribe Paradigm.

I. INTRODUCTION

THe awareness concerning air pollution from CO_2 emissions has increased in recent years, and the realization of a more environment-friendly transportation system is now a worldwide goal. The application of Electric Vehicle (EVs) is considered as an alternative to fossil fuel powered vehicles, while the research and development on EVs including battery design and charging methods have attracted the attention from both commercial and academic communities over the last few years.

Unlike numerous previous works [1] which investigate charging scheduling for EVs already parking at home/Charging Stations (CSs), our research focus turns to managing the charging scenario for on-the-move EVs, by relying on public CSs to provide charging services during their journeys. The latter use case cannot be overlooked as it is the most important feature of EVs, especially for driving experience during journeys. Here, CSs are typically deployed at places where there is high concentration of EVs, such as shopping mall and parking places. On-the-move EVs will travel towards appropriate CSs for charging based on a smart decision on where to charge, in order to experience a shorter waiting time[1] for charging.

In the literature [2]–[4], the decision on where to charge is generally made by Global Controller (GC) in a centralized manner at the power grid side. Here, the GC can access the real-time condition of CSs under its control, through reliable channel including wired-line or wireless communications. Concerning privacy issue, the status of an EV, such as its ID, Status of Charge (SOC) or location [5], [6] will be inevitably released, when that EV sends charging requests to the GC. Concerning system robustness, the charging service will be affected by the single point of failure at the GC side. Alternatively, the CS-selection could be made by individual EV in a distributed manner, based on historically accessed CSs condition information recorded at EV side, such as the case in [7] where EVs will decide their preferred CSs for charging.

In both centralized and distributed cases, necessary information needs to be disseminated between CSs and EVs, such as the expected waiting time at individual CSs in the latter case. In this context, how accurate CSs condition information is accessed by EVs, plays an important role on the charging performance. For example, if the received information regarding estimated waiting time at each CS is substantially outdated, EVs using such obsoletely accessed information might make inappropriate decisions. Above two options require an information dissemination infrastructure for data exchange between EVs and the power grid. In previous works [2]–[4], the cellular network communication (assumed with ubiquitous communication range) is applied in centralized case, for well optimization purpose via real-time information. Cellular infrastructures with good network coverage are typi-

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[1]Apart from the time to wait for charging, the driver will usually leave the EV, handle some other business and get back to the EV later. Therefore, the EV fully charged might not immediately quit the queue, an additional waiting time is needed in most of the cases.

cally applied in the centralized case. Alternatively, a cheaper solution nowadays is the deployment of fixed Road Side Unit (RSU) based on licence-free spectrum such as WiFi, but only with limited network coverage.

In the context of new communication technologies especially 5G [8] for smart transportation and autonomous cars, new mechanisms have been proposed in connected vehicle environments, including Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications [9]. On one hand, V2I based approaches require costs to deploy and maintain dedicated stationary infrastructures, and often they suffer from rigidness due to the lack of flexibility of deploying and possibly relocating fixed RSU facilities. In comparison, the V2V communication option is a more flexible and efficient alternative, which supports necessary data dissemination between connected vehicles when they encounter each other.

It is known that Vehicular Ad hoc NETworks (VANETs) [9] have been deemed as a key enabling technology for connected vehicle applications, ranging from road safety and intelligent transportation systems to on-board Internet access. For information dissemination, the Publish/Subscribe (P/S) [10] paradigm, is a suitable communication paradigm for building applications in VANETs with a highly elastic and scalable nature. Specific to the EV charging applications, the P/S is also applicable where each CS as a publisher which periodically publishes its own status information including queuing time, location, supply price, and capability (i.e., charging speed per unit energy), to EVs as subscribers of the information.

In this article, we present an efficient mobile P/S framework based on V2V communications for disseminating the CSs condition information, to the EVs on-the-move for them to make decisions on CS selection. In contrast to the common practice of deploying stationary RSUs which is a very rigid strategy in dealing with EV mobility, we advocate the concept of Mobility as a Service (MaaS) with a novel scheme of exploiting the predictable mobility of (trusted) transportation vehicles, such as public buses [11], for message relaying in the P/S framework. The advantage is that such mobile intermediaries offer opportunistic encounters with EVs in charging requirement on the road, and also the deployment of such communication facilities on buses can flexibly take into account a wide range of context information, such as pre-planned bus routes, number of buses in service and also their service time intervals.

Since the encounters between an EV with charging requirement and a bus carrying CSs information is opportunistic, it is expected that the information arrived at the EV side cannot be always fresh. Nevertheless, it is understandable that the delivery of such information can be tolerable to a certain degree of delay, as the observation from our previous work [12] where static RSUs are used for information relay. Compared to using ubiquitous but certainly more expensive cellular network communication which will not experience any significant delay in information access, the delay due to opportunistic communication certainly has influence on how fresh the information is accessed by EVs for making CS-selection decisions. For instance, a decision making based on the obsolete information that is due to long delay, may mislead

the EV towards the highly congested CS for charging.

It is worth highlighting that this article focuses on the impact of the charging management on the EVs (e.g., Quality of Experience (QoE) in terms of how long each EV driver needs to wait for charging) and not on the power grid (i.e., valley filling [13], [14]). To our best knowledge, this piece of work represents the very first attempt in the literature that proposes MaaS through V2V technologies for enabling smart transportation and power grid services in terms of EV charging management. Our specific technical contributions are as follows:

MaaS Driven P/S Communication Framework Provisioning via Transportation Buses: Benefiting from exploiting buses to relay CSs condition information, the flexibility of entire mobile P/S based charging management system can be enhanced. Here, opportunistic encounters between buses and EVs offer higher chances for the latter in accessing CSs information, compared to the fixed RSUs case. In this context, we analyze various factors that affect the probability an EV could access the published CS information, through encountering a number of buses during the journey. Based on this analysis for opportunistically accessing information via the proposed mobile P/S communication framework, the Available Time for Charging (ATC) of CSs is published to EVs for making charging decisions.

Study of EV Charging Management Via Remote Reservation: Intuitively, since the ATC can be easily affected by traffic condition uncertainty, congestion may occur at CS side if many EVs travel towards the same CS for charging in a short period of time. With this in mind, we further study the feasibility of bringing remote reservation service, based on the above mobile P/S communication framework. Here, those EVs which are travelling towards their selected CSs for charging, will additionally send their charging reservations. This anticipated information, including when an EV is expected to arrive and how long it will need to fully recharge its battery, is harvested and used by CSs in order to further publish their expected conditions in the near future. Such reservation information publication from EVs to a CS, is aggregated (subject to the tolerated delay constraint) and bridged by buses for reducing signalling cost (incurred by the necessary data transmission over more expensive wireless links, e.g., cellular network communication) between moving buses and the power grid. While the CS with the minimum value of Expected Earliest Time Available for Charging (EETAC) is then selected by EVs need charging services. Results show that bringing such anticipated reservation information as well as aggregation, achieves an improved charging performance at CS and EV sides while with a low communication cost.

The rest of the article is organized as follows. In Section II we present the related work, followed by Section III in which the proposed Pull Mode communication framework to support basic EV charging management scheme. The reservation based charging management based on the Advanced Pull Mode communication framework is proposed in Section IV. Finally, we conclude our work in section V.

II. RELATED WORK

A most recent survey [2] has identified two technical branches for EV charging management. On the one hand, majority of works in literature [1] address the problem of regulating the EV charging, such as minimizing peak load/cost, flattening aggregated demands or reducing frequency fluctuations. On the other hand, a few works are more concerned with minimizing the charging waiting time of EVs.

In the latter branch, the work in [3] relies on a GC connected to all CSs, where EVs requiring for charging will send their requests to GC for arrangement. The work in [4] compares the schemes to select the CS based on the closest distance and minimum waiting time, where results show that the latter performs better given high EVs density under city scenario. Besides, under high way scenario [15], CSs are enable to relay the information such as waiting time, EVs' reservations as well as EVs' route information. In [16], the CS with a higher capability to accept charging request from on-the-move EV, will advertise this service with a higher frequency, while EV senses this service with a decreasing function of its current battery level. In light of this, the EV with a lower battery volume will more frequently sense the service from CS. The CS-selection scheme in [17] adopts a pricing strategy to minimize congestion and maximize profit, by adapting the price depending on the number of EVs charging at each time point. Note that previous works on CS-selection can usually be integrated with route planning, such as the work in [18] predicts congestion at charging stations and suggests the most efficient route to its user.

The P/S paradigm [10] mainly offers communications decoupled in space that subscribers do not need to know publishers and vice-versa, and potentially in time if the system is able to store events for clients which are temporally disconnected, such as the intermittent connection resulting from rapid topology changes and sparse network density in Delay/Disruption Tolerant Networks (DTNs) [19]. In particular, a P/S system can be Push-based, Pull-based. The Push Mode provides tight consistency and stores minimal, in which information is automatically published to subscribers. The Pull Mode can be more responsive to user needs, by replying the information if receiving query from user. In particular, based on the Pull Mode communication framework, we have brought the RSU for relaying the CSs condition information and EVs' charging reservations in [12]. In this article, essential contributions over that previous work are as follows:

1) As the substantial novelty in this article, we bring the public buses as mobile access points for disseminating CSs condition information. The main research motivation here is the flexibility and low network configuration cost (as highlighted in Introduction section). With analysis and corresponding results, we then claim the benefit of bringing buses over RSUs (as brought in [12]) at the end of Section III. In particular, in this article we further discuss the feasibilities of other alternative options, explicitly concerning the difficulty of maintaining end-to-end connections under VANETs communication scenario. Such a discussion (with peak load analysis and corresponding results), shows the soul advantage of our proposed P/S based VANETs communication framework for well managed EV charging, over other alternative cases. Driven by this, we then bring our three major novel technique contributions.

2) In proposed Pull Mode, the Available Time for Charging (ATC) is investigated, by tracking what time a charging slot of CS will be free. Such precise information related to each charging slot of a CS, is explicitly disseminated through the P/S based VANETs communication framework, due to the highly dynamic and opportunistic vehicle encounters. This is different from [12] which only addresses the EVs queuing time at a CS (which is just an abstract information about CS). Therefore, the ATC as disseminated here aims to lead a user friendly CS-selection policy, concerning the information is accessed from opportunistic way.

3) Further to the proposed P/S driven VANETs communication framework, in the proposed Advanced Pull Mode, the intelligence on estimating the Expected Earliest Time Available for Charging (EETAC) at CS, is within a time window (related to CS publication frequency). In more detail, we decouple the time window into several discrete time slots, and estimate the corresponding EETAC at given time slot. In [12], each CS just publishes its associated EVs reservations, to all on-the-move EVs through RSUs. The estimation of expected charging waiting time is not driven by the time window, let alone linking the expected waiting time to each discrete time slot. Therefore, our proposal in this article can capture and predict the status of CS more accurately than [12].

4) Finally, the aggregation of EVs charging reservations is designed, in order to reduce the communication cost at CS side. In comparison to [12], there is no aggregation of EVs charging reservations, which thereby brings much communication cost. The motivation of this is to alleviate the uncertain communication load due to opportunistic encounter between vehicles. Instead we transfer the reservation reporting from an uncertain and opportunistic manner, into a stable and periodical manner (tightly related to CS publication frequency).

III. ON-THE-MOVE EV CHARGING MANAGEMENT BASED ON PULL MODE

A. Overview of Pull Mode Communication Framework

TABLE I
TOPIC: ATC UPDATE

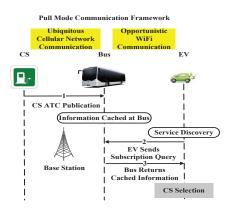| Topic Name (Many-to-Many)	Publisher	Subscriber	Payload
ATC Update	CSs	EVs	<"CS-1 ID", "Publication Time Stamp", "CS-1 ATC">
			<"CS-2 ID", "Publication Time Stamp", "CS-2 ATC">
			<"CS-3 ID", "Publication Time Stamp", "CS-3 ATC">
			<"CS-4 ID", "Publication Time Stamp", "CS-4 ATC">

Fig. 1. Pull Mode Communication Framework

Due to high mobility, it is difficult to maintain a contemporaneous end-to-end connection between the CS and EV through bus. The proposed P/S communication framework is based on the Pull Mode, in which the communication is asynchronous, by caching the CS condition at bus side for future access. Here, the originally published CS condition information can be cached at intermediate buses. Whenever there is a future encounter between a bus and EV, EV can access the cached information by sending a query. Three network entities are involved:

- The Electric Vehicle (EV) as subscriber, sends query to subscribe to the information relayed by buses. Based on the access information, the EV needs charging would select a CS as charging plan.
- The Charging Station (CS) as publisher, periodically publishes its condition information to the legitimate buses.
- The bus is as a mobile entity to aggregate all CSs condition information and caches it in local storage. This information is further accessed by EVs for making CS-selection decisions.

The Pull Mode of P/S communication framework envisioning for EV charging scenario (with buses to relay information) is introduced as follows, with the time sequences illustrated in Fig.1:

1) **Step 1:** Each CS periodically publishes its condition information, e.g, Available Time for Charging (ATC) using "ATC UPDATE" topic defined in TABLE I, to all the designated buses (that are involved in message dissemination in the P/S system) through cellular network communication. In order to make efficient usage of the cellular link equipped at the bus side, the bus will aggregate the information in relation to each CS, as illustrated in the payload of topic, and then the aggregated information about all CSs condition is cached in the storage of bus. Note that once a new value has been received depending on CS publication frequency, it will replace the obsolete values in the past, that are not necessarily maintained.

2) **Steps 2-3:** Given an opportunistic encounter between pairwise EV and bus, the EV could discover whether the bus has a service to provide CSs condition, based on existing service discovery, e.g., the location based

scheme [20] proposed for VANETs. Then the EV sends an explicit query to the bus, via the same topic through WiFi communication. Upon receiving this query, that bus then returns its latest cached CSs condition information to that EV. With this knowledge, an EV requiring charging service can make its own decision on where to charge.

The information exchange between CSs and EVs through buses is based on above introduced Pull Mode based communication framework, where the publication of all CSs is synchronized. Under the city scenario, each public bus is as an intermediate entity for bridging the information flow from CSs to EVs. In Fig.1, The role of opportunistic WiFi is effectively used as the default radio communication technology to enable the short-range communication between EVs and their encountered buses for information dissemination operations. This can be envisioned for the real-world application, where buses providing WiFi communication (already been applied in real world bus system), behave as mobile access points for information dissemination. If with a low battery status, EVs will then decide where to charge based on their gathered information from buses.

B. Assumption

We assume all EVs could obtain the location of each CS, from On-Board-Units (OBUs). As a type of public transportation, the number of buses in network is normally less than that of EVs. The mobility of bus is restricted by its predefined route, while the bus may temporarily stop once its deterministic route is traversed. The credibility of information from CSs is required for the hazard-free decision of EVs. As a result, all messages must be digitally signed by CSs and later can be verified by EVs before making CS-selections.

C. Analysis on Pull Mode Communication Framework

For the purpose of generalization, we assume there are one EV and M buses moving on a two-dimensional torus within the area of $\left(\sqrt{Z} \times \sqrt{Z}\right)$, where Z is the network area. It has been shown that a number of popular mobility models as well as more realistic, synthetic models are based on (approximately) exponential encounter characteristics. Particularly, realistic VANETs mobility models have already shown an exponential encounter rate between vehicles [21], and has been adopted by previous works addressing opportunistic communication. Although the bus mobility is somehow predictable (due to predefined route), the Independent and Identically Distributed (IID) exponential encounter between buses has been modelled and tested for researches on DTN routing [22]. Here, since the EV movement is random before it needs charging service, the Expected Meeting Time (EMT) between a bus and EV is approximately to be IID exponential random variables.

1) Pull Mode: We model an event that the EV could access the condition information published from a single CS, by encountering at least one of M buses in network. Here, given the CS publication frequency Δ (how often or the time

interval that each CS publishes its information) and caching nature of Pull Mode, the probability that EV could access the information from any bus, depends on: 1) whether this bus has cached the information published from CS. 2) whether there is an encounter between EV and that bus.

The analysis is decoupled as follows:

- Referring to previous analysis on opportunistic encounter [22], [23], the time until EV encounters any one of M buses, is given by $\frac{EMT}{M}$ since the encounter is identical.
- Excluding that previously encountered bus, the time until the EV encounters another one of $(M-1)$ buses is given by $\frac{EMT}{M-1}$.
- By generalizing the above steps, the time until the EV encounters the last bus is given by $\frac{EMT}{M-(M-1)} = EMT$.

Therefore, the above stated probability is given by a ratio of the encounter time between pairwise EV and bus, to the publication frequency Δ. If there are M buses in network, the probability $P_{(pull)}$ that EV can access information from at least one of M buses is derived as:

$$P_{(pull)} = 1 - \prod_{i=0}^{M-1}\left(1 - \frac{EMT}{(M-i)\times\Delta}\right) \quad (1)$$

Here, the probability $\frac{EMT}{(M-i)\times\Delta}$ that EV can access information from the ith bus, depends on the CS-publication frequency Δ, and the encounter time $\frac{EMT}{M-i}$ between EV and that bus. Note that $\left(\frac{EMT}{(M-i)\times\Delta} = 1\right)$, only if $\frac{EMT}{M-i}$ is longer than the CS publication frequency Δ. Otherwise, $\left(\frac{EMT}{(M-i)\times\Delta} = 0\right)$.

Here, authors in [22] have derived an approximated form for EMT, where $EMT = 0.5Z\left(0.34\ln Z - \frac{2^{R+1}-R-2}{2^R-1}\right)$ is related to network size Z and nodal transmission range R. Ideally, the configuration on Z and R should satisfy the condition that $(EMT \geq \Delta)$. This means that the EV can obtain the information by encountering the last one of M buses in network, as given by $\left(\frac{EMT}{\Delta} = 1\right)$. Therefore, concerning communication and network entity aspects, a high possibility to access information from at least one of buses in network, depends on :

- An increased CS publication frequency Δ.
- An increased communication range R.
- An increased number of buses M.

We further discuss other two alternative cases communication frameworks:

2) Alternative Case-1 (Real-time Information Access Via Buses): Illustrated in Fig.2, there is no periodical CS publication. However, the real-time CS condition information is accessible, when there is encounter between pairwise EV and bus. Here, the communication is synchronous (simultaneously between CS and EV via bus), as there is no information cached at bus side. This can be referred to the application, where bus (connected to CSs through cellular network communication) behaves as a mobile access point for EVs to access CSs information. Similar to previous analysis, we have:

$$P_{(ac1)} = 1 - \prod_{i=0}^{M-1}\left(1 - \frac{1}{M-i}\right) \quad (2)$$

where $\frac{1}{M-i}$ is the probability that EV encounters each one of M buses, given the identical nodal mobility. Recall that $(EMT \geq \Delta) \Rightarrow \left(\frac{EMT}{\Delta} = 1\right)$ already holds true for Pull Mode communication framework, then we have $\left(P_{(pull)} \leq P_{(ac1)}\right)$.
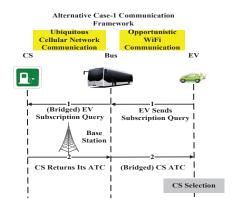

Fig. 2. Alternative Case-1 Communication Framework

3) Alternative Case-2 (Directly Periodical Publication to EVs): Illustrated in Fig.3, each CS periodically (with frequency Δ) publishes its condition information to EVs through cellular network communication, while the bus does not behave any role in this case. Since EV can always obtain information with each CS publication, the information access probability is $\left(P_{(ac2)} = \frac{1}{\Delta}\right)$. It is highlighted that if with an extremely frequent publication frequency, as given by a small Δ, this situation is close to the Centralized Case illustrated in Fig.4. In such case, the CS-selection is made instantly by Global Controller (GC) which owns real-time CS condition information, whenever the GC receives a charging request from EVs.

Fig. 3. Alternative Case-2 Communication Framework

4) Discussion: In TABLE II, we provide peak load analysis assuming all EVs need charging simultaneously, here N_{bus} and N_{ev} are number of buses and EVs in network. Easy to observe, Alternative Case-2 brings much load than Pull Mode at the CS side, given the condition $(N_{bus} < N_{ev})$ in reality. Besides, although the peak load at the CS side under Alternative Case-1 is affected by mobility factor $P_{(ac1)}$, it is proportional to N_{ev}, same as that at the GC side under the Centralized Case. Due to decoupling between publishers and subscribers, the

Fig. 4. Centralized Case Communication Framework

TABLE II
PEAK TRAFFIC ANALYSIS

Communication Framework	Peak Load for Information Publication at CS/GC
Pull Mode	$O\left(\frac{N_{bus}}{\triangle}\right)$
Alternative Case-1	$O(P_{(ac1)} \times N_{ev})$
Alternative Case-2	$O\left(\frac{N_{ev}}{\triangle}\right)$
Centralized Case	$O(N_{ev})$

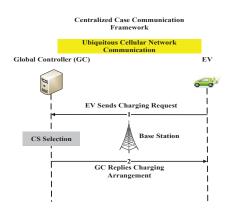end-to-end connections between CSs and EVs are avoided. Instead, an EV just accesses information from a bus which is close to it. As such, we can have scalability (the number of connections at CS sides does not depend on the number of EVs), as the benefits of P/S based communication against point-to-point communication.

Downsides of other communication frameworks are listed as follows:

- Even though the Alternative Case-1 achieves a higher information access probability than the Pull Mode, the former requires a contemporaneous end-to-end connection between CSs and EVs through buses, and brings more number of connections at the CS side. Therefore, Alternative Case-1 may be infeasible in VANETs due to the high mobility, where maintaining end-to-end connections is challenging.
- Although the Alternative Case-2 does not need to bring additional network entities, it relies on ubiquitous cellular network communication and needs broadcast capability, which is even more expensive than the Pull Mode utilizing short range WiFi communication.
- In contrast to the Pull Mode and above two Alternative Cases, it is privacy sensitive to release EV status information (e.g., ID, location) in Centralized Case. In spite that the Centralized Case as the ideal case for communication pattern relies on real-time condition, our research investigates that a distributed communication framework, as our proposed Pull Mode, is able to achieve a close performance by controlling how frequent CSs should publish their condition information.

D. Estimating the Available Time for Charging

TABLE III
LIST OF NOTATIONS

ATCLIST	Output list including available time per charging slot at CS
T_{cur}	Current time in the network
δ	Number of charging slots at CS
N_W	Number of EVs waiting for charging at CS
N_C	Number of EVs under charging at CS
E_{ev}^{max}	Full volume of EV battery
E_{ev}^{cur}	Current volume of EV battery
β	Charging power at CS
T_{ev}^{fin}	Charging finish time of EV

Algorithm 1 EstimateAvailableTimeForCharging

1: **if** no EV is under charging **then**
2:    add T_{cur} in ATCLIST with δ times
3: **end if**
4: **for** $(i = 1; i \leq N_C; i++)$ **do**
5:    ATCLIST.ADD $\left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta} + T_{cur}\right)$
6: **end for**
7: **if** $(N_C < \delta)$ **then**
8:    **for** $(j = 1; j \leq (\delta - N_C); j++)$ **do**
9:        ATCLIST.ADD(T_{cur})
10:    **end for**
11: **end if**
12: sort ATCLIST with ascending order
13: **if** no EV is waiting for charging **then**
14:    **return** ATCLIST
15: **else**
16:    sort the queue of N_W according to FCFS
17:    **for** $(k = 1; k \leq N_W; k++)$ **do**
18:        $T_{ev(k)}^{fin} = $ ATCLIST.GET(0) $+ \frac{E_{ev(k)}^{max} - E_{ev(k)}^{cur}}{\beta}$
19:        replace ATCLIST.GET(0) with $T_{ev(k)}^{fin}$
20:        sort ATCLIST with ascending order
21:    **end for**
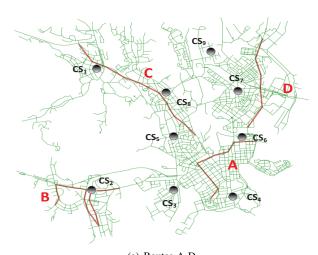22:   **return** ATCLIST
23: **end if**

For estimating the available time for all charging slots at a CS, we consider two types of queues respectively. Those EVs which are under charging are characterized in the queue of N_C, while those still waiting for charging are characterized in the queue of N_W. As presented at line 2 in Algorithm 1, the current time in network as denoted by T_{cur} is estimated as the available charging time for each charging slot, if none of EVs is under charging. In this case, the ATCLIST containing a number of T_{cur} is directly returned. This means those charging slots of CS are currently available.

In general, Algorithm 1 starts from processing each EV_i (in the queue of N_C), where its time duration $\left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta}\right)$ to be fully recharged will be aggregated with T_{cur}. This sum value is as the charging finish time of EV_i, and it is inserted into ATCLIST. Upon the above processing for those EVs under charging, the presentation between lines 7 and 11 implies that all charging slots have not been fully occupied, because there are still $(\delta - N_C)$ slots free for charging. In this case, T_{cur} is as the available charging time for these unoccupied charging slots.
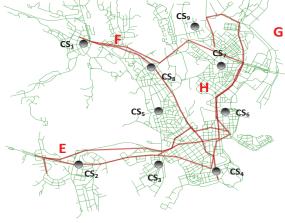
Then, Algorithm 1 will return the available time for charing per charging slot, either if the number of EVs waiting for charging is 0 as the condition stated at line 13, or a loop operation for each EV_k waiting for charging has been processed

as stated between lines 17 and 21.

In the latter case, the loop operation starts from sorting the queue of N_W, based on the FCFS charging scheduling order. Meanwhile, the ATCLIST containing when the charging of those EVs (in the queue of N_C) will be finished, is initialized with an ascending order. Here, the earliest available time is at the head of ATCLIST, as denoted by ATCLIST.GET(0). Normally, the charging finish time $T_{ev_{(k)}}^{fin}$ of each EV_k (in the queue of N_W) will replace with ATCLIST.GET(0). At line 18, $T_{ev_{(k)}}^{fin}$ is calculated as the sum of time to start charging as denoted by ATCLIST.GET(0), and battery charging time given by $\left(\frac{E_{ev(k)}^{max} - E_{ev(k)}^{cur}}{\beta} \right)$. Furthermore, the ATCLIST will be sorted with ascending order once processing an EV_k for each loop, such that the earliest time for charging obtained by ATCLIST.GET(0) is used in each loop. The above loop operation ends when all EV_k have been processed, and then the ATCLIST is returned at line 22.

E. Performance Evaluation

(a) Routes A-D

(b) Routes E-H

Fig. 5. Simulation Scenario

1) Scenario Configuration: We use the Opportunistic Network Environment (ONE) [24] version 1.4.1 for evaluation, which is originally for opportunistic communication research purpose in DTNs [19]. The entire charging system has been implemented in ONE. The underlying city scenario is based on the Helsinki in Finland with 8300×7400 m^2 area, containing four main districts A-D. Besides, there are three overlapping districts considering movements between the districts A and other districts, and one district covers the whole simulation area. In detail, district E includes A and B, F includes A and C, G includes A and D, and H covers from A to D. Every district is assigned its own bus route, shown in Fig.5(a) and Fig.5(b).

400 EVs with $[2.7 \sim 13.9]$ m/s variable moving speed are initialized considering road safety in a city. The configuration of EVs follows the charging specification {Maximum Electricity Capacity (MEC), Max Travelling Distance (MTD), Status Of Charge (SOC)}. Here, the electricity consumption for the Traveled Distance (TD) is calculated based on $\frac{MEC \times TD}{MTD}$. We configure the following EVs with 100 for each type: Coda Automotive [25] {33.8 kWh, 193 km, 30%}, Wheego Whip [26] {30 kWh, 161 km, 40%}, Renault Fluence Z.E. [27] {22 kWh, 160 km, 50%}, Hyundai BlueOn [28] {16.4 kWh, 140 km, 60%}.

Besides, 9 CSs are provided with sufficient electric energy and 3 charging slots through entire simulation, using the fast charging rate of 62 kW referring to [17]. Those parking EVs will depart from CS once their batteries are fully charged, by referring to [17]. The CS publication frequency is 300s by default. 5 buses with $[7 \sim 10]$ m/s variable moving speed are configured on each route. Buses will stop with a time duration ranging between 0s and 120s. We consider a low power WiFi technique with a 300m transmission range for EVs to communicate with buses.

2) Underlying EV Charging Management System: The EV reaching a threshold on its residual battery charge applies a policy to select a dedicated CS for charging, using the information accessed from encountered buses. Note that, this EV might have received information for several times before it reaches the threshold for requesting charging. The underlying EV charging scheduling about when to charge, is based on the First Come First Serve (FCFS) order. This means that the parking EV with an earlier arrival time will be scheduled with a higher charging priority. If the CS is fully occupied by other parking EVs, any incoming EV should wait until one of charging slots is free.

Based on the aforementioned Pull Mode communication framework for publishing the CS available charging time, EVs will have a historical record about CSs' available charging time. The CS-selection policy follows:

- By recursing Algorithm 1 for each CS, its available time for charging per charging slot is obtained. The general decision on where to charge is to find the CS with the earliest available time for charging, as given by ATCLIST.GET(0).
- In the worst case, the EV would select a CS with the closest geographic distance to the CS as remedial solution, if none of the information in relation to any CS is accessed from buses. This situation typically happens when that EV misses all encounters with buses in network.

3) Evaluation Metrics: Here, **Proposal-Pull Mode**, **Proposal-AC1**, **Proposal-AC2** and **Centralized Case**, discussed in Section III, are based on the above underlying charging system. Note that only the real-time information can be always accessible in the **Centralized Case**. The performance metrics are:

- **Average Waiting Time** - The average period between the time an EV arrives at the selected CS and the time it finishes recharging its battery. This is the metric at user side as for EV.
- **Number of Charged EVs** - The total number of fully charged EVs in the network. This is the metric at grid side as for CS.
- **Information Access Times** - The total number of times that all EVs access information from buses. This is directly related to the probability that each EV accesses information from buses as analysed in Section III.
- **Average Data Error** - The average value of the difference between the current waiting time at CS side and that recorded at EV side, only calculated when an EV makes its individual selection decision.
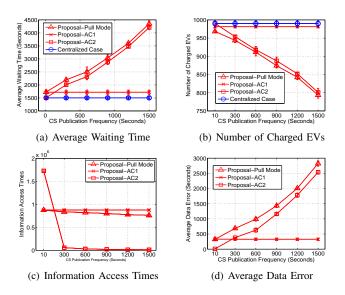

(a) Average Waiting Time

(b) Number of Charged EVs

(c) Information Access Times

(d) Average Data Error

Fig. 6. Influence of CS Publication Frequency

4) Influence of CS Publication Frequency: In Fig.6(a) and Fig.6(b), in case of the Pull Mode and Alternative Case-2, all EVs experience an increased average waiting time and the number of charged EVs is reduced with an infrequent CS publication. This is because that using an outdated information affects the accuracy on where to charge, reflected by the information access times shown in Fig.6(c). As such, in Fig.6(d), there is a huge information error between that performance given 300s and 1500s CS publication frequencies. In particular, since the CS-selection decision could be made instantly using real-time CS condition information, the performance under the Centralized Case achieves the shortest average waiting time. Meanwhile, the Proposal-AC1 is not affected by publication frequency, since it only relies on the opportunistic encounter to publish real-time CS information. Since both the Proposal-Pull Mode and Proposal-AC2 depend on the CS publication frequency, their performance is degraded

(a) Average Waiting Time

(b) Number of Charged EVs

(c) Information Access Times

(d) Average Data Error

Fig. 7. Influence of Transmission Range

(a) Average Waiting Time

(b) Number of Charged EVs

(c) Information Access Times

(d) Average Data Error

Fig. 8. Influence of Entities Density

gradually. In comparison, the former depends on periodical CS publication and opportunistic encounter between EVs and buses, whereas the latter only depends on the CS publication frequency. This is the reason that the latter outperforms the former, as EVs can always access information within CSs publication. In particular, in Fig.6(c), although the Pull Mode brings a higher load given the infrequent CS publication, it outperforms the Alternative Case-2 given frequent CS publication. Since a frequent CS publication leads to an improved charging performance (e.g., shorter charging waiting time and higher number of charged EVs), we claim the efficiency of Pull Mode over Alternative Case-2 for a well-managed EV charging.

5) Influence of Transmission Range: We vary the transmission range, where results in Fig.7(a), Fig.7(b), Fig.7(c) and Fig.7(d) show that the times to access CSs condition information is reduced due to a smaller transmission range. As such, the charging performance is inevitably degraded, where

only the Pull Mode and Alternative Case-1 suffer from this, as they rely on buses to relay information publication.

6) Influence of Entities Density: Regarding flexibility comparison, we further randomly deploy a number of RSUs on each bus route. Fig.8(a), Fig.8(b), Fig.8(c), Fig.8(d) show that, in case of low entities density, applying buses (mobile entities) as a flexible option, achieves a better performance than that applying RSUs (stationary entities). This is due to the mobility of buses bringing more chances for EVs to access information. The key observation is that, applying (8×1) buses is able to achieve a close charging performance shown in Fig.8(a), Fig.8(b) by deploying (8×3) RSUs. Meanwhile, their gap is close in case of 5 buses/RSUs per route, due to that a high entities density is able to guarantee a good information access probability.

IV. ON-THE-MOVE EV CHARGING MANAGEMENT BASED ON ADVANCED PULL MODE

A. Overview of Advanced Pull Mode Communication Framework

In advanced communication framework, the EV which has made its CS-selection further sends its charging reservation, including when to reach and how long its expected charging time will be at the selected CS. Apart from the information flow relayed from the CSs to EVs in Pull Mode, this charging reservation will be relayed to the EV's selected CS, through an opportunistically encountered bus in Advanced Pull Mode.

With this anticipated EVs' charging reservations involved in Advanced Pull Mode, CS intelligently computes and publishes its Expected Earliest Time Available for Charging (EETAC), associated with a number of continuously discrete time slots in future. This is different from the basic Pull Mode in Section III, in which only the Available Time for Charging (ATC) is published from the CS. Here, we extend the functionality of bus, to aggregate EVs' reservations and then reports them to the corresponding CS. Rather than instantaneously relaying the reservation from each EV to its selected CS, the proposed aggregation function aims to reduce the communication cost at the CS side.

With anticipated EVs' reservations, the charging plans of EVs can be managed in a coordinated manner. For example, if a CS has been reserved by many on-the-move EVs for charging purpose, that CS predicts and publishes its status in a near future. Other EVs need charging services would identify the congestion status of CS, and thus select an alternative CS for charging purpose. Here, the CS-selection policy (based on the EETAC published from CSs) is to find the CS at which the EV (needs charging service) would experience the shortest charging waiting time.

B. Procedure of Advanced Communication Framework

A typical procedure is illustrated as follows:

- **Steps 1-3:** These steps are still executed through the Pull Mode in Section III. Note that although the Advanced Pull Mode also relies on the Pull Mode for notifying CSs condition information to EVs, the information disseminated (e.g., EETAC through topic "EETAC Update"
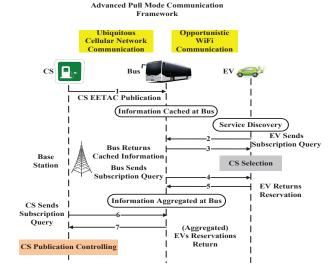

Fig. 9.   An Overview of Advanced Communication Framework

TABLE IV
TOPIC: EETAC UPDATE

Topic Name (Many-to-Many)	Publishers	Subscribers	Payload
EETAC Update	CSs	EVs	<"CS-1 ID", "Publication Time Stamp", "CS-1 EETAC">
			<"CS-2 ID", "Publication Time Stamp", "CS-2 EETAC">
			<"CS-3 ID", "Publication Time Stamp", "CS-3 EETAC">
			<"CS-4 ID", "Publication Time Stamp", "CS-4 EETAC">

topic in TABLE IV) herein is different from the ATC involved in Pull Mode.

- **Steps 4-5:** Based on accessed information, any EV requiring charging service can make its own decision on where to charge, and further publishes its charging reservation to an encountered bus. Here, each bus as subscriber, sets a "RESERVATIONS AGGREGATION" topic defined in TABLE V and uses Pull-based P/S communication to access the reservations from encountered EVs. The number of this topics depends on number of buses, as each bus uses its individual topic to collect EVs' reservations.

TABLE V
TOPIC: RESERVATIONS AGGREGATION

Topic Name (Many-to-One)	Publishers	Subscriber	Payload
Reservations Aggregation	EVs Made CS-selection Decisions	Bus	<"Reservation Detailed in TABLE VIII">

- **Steps 6-7:** At CS side, it accesses aggregated EVs' reservations through Pull-based P/S communication via a "AGGREGATED RESERVATIONS UPDATE" topic defined in TABLE VI. The number of this topics depends on number of CSs, as aggregated reservations are in line with an explicit CS. Note that all aggregated EVs' reservations (in relation to an explicit CS) stored at buses should be published to that CS before its next publication time stamp, given by $(T_{pre} + \triangle)$. Recalling that T_{pre} is

the time stamp for previous CS publication, while $\triangle$ is the CS publication frequency. Such information triggers all buses connected (through cellular network communication) to an explicit CS, to publish their aggregated EVs' reservations related to that CS. The CS computes its updated EETAC, for publication at next publication time slot.

TABLE VI
TOPIC: AGGREGATED RESERVATIONS UPDATE

Topic Name (Many-to-One)	Publishers	Subscriber	Payload
Aggregated Reservations Update	Buses	CS	<Next Time Stamp for CS Publication, Aggregated "Reservation Detailed in TABLE VIII">

TABLE VII
LIST OF NOTATIONS

T_{ev}^{arr}	EV's arrival time at CS
T_{ev}^{tra}	EV's travelling time to reach CS
T_{ev}^{cha}	Expected charging time upon arrival of EV
S_{ev}	Moving speed of EV
α	Electric energy consumed per meter
N_R	Number of EVs reserved for charging at CS
N_E	Number of entries for expected waiting time publication
TS	A time slot of N_E
EETAC$_{TS}$	The given EETAC at TS
REVLIST	Input list including a number EVs made reservation at CS

C. Detail of EV's Charging Reservation

The reservation information is relayed from the EV which has made CS-selection decision, to its selected CS through an encountered bus. This information includes the ID of selected CS, arrival time at that CS, and EV's expected charging time at there. Specifically:

Arrival Time: Based on the travelling time T_{ev}^{tra} calculated from the current location of EV, to its selected CS via the shortest road path, the arrival time T_{ev}^{arr} at that CS is given by:

$$T_{ev}^{arr} = T_{cur} + T_{ev}^{tra} \tag{3}$$

Expected Charging Time: The expected charging time T_{ev}^{cha} at the selected CS is given by:

$$T_{ev}^{cha} = \frac{E_{ev}^{max} - E_{ev}^{cur} + S_{ev} \times T_{ev}^{tra} \times \alpha}{\beta} \tag{4}$$

Here, $(S_{ev} \times T_{ev}^{tra} \times \alpha)$ is the energy consumed for movement travelling to the selected CS, based on a constant α (depending on a certain type EV) measuring the energy consumption per meter.

TABLE VIII
CHARGING RESERVATION OF EV$_2$

EV ID	Selected CS	Arrival Time	Expected Charging Time
EV$_2$	CS$_3$	3060s	730s

Following above definition of EV charging reservation, Fig.10 illustrates the intelligence of charging management. Basically, the EETAC could be estimated either with or
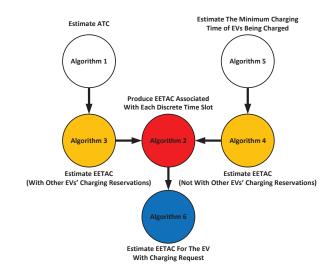

Fig. 10.   Computation Logic

without EVs' charging reservations, as detailed in Algorithm 3 and Algorithm 4 respectively. Then, Algorithm 2 will produce the EEATC associated with each discrete time slot, where these time slots are decoupled from an estimation time window (based on CS publication frequency $\triangle$). With this knowledge published from CSs, the EV needs charging then makes CS-selection decision, via Algorithm 6.

D. CS Publication Controlling

TABLE IX
FORMAT OF INFORMATION PUBLICATION FROM CS SIDE

CS ID		
CS$_1$		
Publication Time Slot		
3160s		
EETAC Per Discrete Time Slot		
Entry	Discrete Time Slot	EETAC
1	3160s	3223s
2	3360s	3467s
3	3560s	3711s

Upon receiving EVs' reservations it is targeted, each CS computes its **Expected Earliest Time Available for Charging (EETAC)** for a number of continuously discrete time slots in a near future. Here, depending on CS publication frequency $\triangle$ within which there are N_E time slot based entries, the interval between adjacent time slots is calculated by $\frac{\triangle}{N_E}$.

Algorithm 2 is run for each CS, to generate its corresponding EETAC at a number discrete time slots in future. Here, the time slot at the ith entry, is calculated by $\text{TS}_i = \left(T_{cur} + (i-1) \times \frac{\triangle}{N_E} \right)$, where T_{cur} is the current time in network. Here, TS_i indicates a discrete time slot in future, since the current time T_{cur}. The CS publication controlling is presented as follows:

- The EV$_j$ (in the queue of N_R) which has made reservation for its selected CS while its arrival time $T_{ev(j)}^{arr}$ is earlier than the TS_i, will be recorded into a

Algorithm 2 CS Publication Controlling

1: **for** $(i = 1; \ i \leq N_E; \ i + +)$ **do**
2: $\quad$ $\text{TS}_i = \left(T_{cur} + (i-1) \times \frac{\Delta}{N_E} \right)$
3: $\quad$ **if** $(N_R \neq 0)$ **then**
4: $\quad\quad$ sort the queue of N_R according to FCFS
5: $\quad\quad$ **for** $(j = 1; \ j \leq N_R; \ j + +)$ **do**
6: $\quad\quad\quad$ **if** $\left(T^{arr}_{ev(j)} < \text{TS}_i \right)$ **then**
7: $\quad\quad\quad\quad$ REVLIST.ADD(EV$_j$)
8: $\quad\quad\quad$ **end if**
9: $\quad\quad$ **end for**
10: $\quad\quad$ **if** (REVLIST.SIZE $\neq 0$) **then**
11: $\quad\quad\quad$ EETAC$_{\text{TS}_{(i)}}$ = EETAC–Computation (REVLIST, TS$_i$) via Algorithm 3
12: $\quad\quad$ **else**
13: $\quad\quad\quad$ EETAC$_{\text{TS}_{(i)}}$ = EETAC–Computation (TS$_i$) via Algorithm 4
14: $\quad\quad$ **end if**
15: $\quad$ **else**
16: $\quad\quad$ EETAC$_{\text{TS}_{(i)}}$ = EETAC–Computation (TS$_i$) via Algorithm 4
17: $\quad$ **end if**
18: $\quad$ add $\left\langle \text{TS}_i, \ \text{EETAC}_{\text{TS}_{(i)}} \right\rangle$ in entry i
19: **end for**

---

list, namely REVLIST. Given that a number of EVs (in the queue of N_R) will arrive at the selected CS, before the TS$_i$ given by $\left(T^{arr}_{ev(j)} < \text{TS}_i \right)$ at line 6, the given EETAC estimated at TS$_i$, as denoted by EETAC$_{\text{TS}_{(i)}}$ is calculated via Algorithm 3.

Note that, running Algorithm 3 requires that there is at least one EV$_j$ with an earlier arrival time than TS$_i$, given by the condition at line 10 in Algorithm 2. Otherwise, Algorithm 4 is applied to compute the EETAC if the above condition is not met, by only considering those EVs already locally parking at the selected CS.

- Alternatively, Algorithm 4 is also applied if there has not been any EV making reservation for the selected CS, as presented between lines 15 and 16.

Then, a pair of $\left\langle \text{TS}_i, \ \text{EETAC}_{\text{TS}_{(i)}} \right\rangle$ stating the "$\langle$Time Slot, EETAC at This Time Slot$\rangle$" will be recorded for information publication. Details regarding Algorithm 3 and Algorithm 4 are introduced as follows:

Algorithm 3 EETAC–Computation(REVLIST, TS)

1: sort the queue of N_R according to FCFS
2: generate ATCLIST via Algorithm 1
3: **for** $(i = 1; \ i \leq N_R; \ i + +)$ **do**
4: $\quad$ **if** REVLIST contains EV$_i$ **then**
5: $\quad\quad$ sort ATCLIST with ascending order
6: $\quad\quad$ **if** $\left(\text{ATCLIST.GET}(0) > T^{arr}_{ev(i)} \right)$ **then**
7: $\quad\quad\quad$ $T^{fin}_{ev(i)} = \left(\text{ATCLIST.GET}(0) + T^{cha}_{ev(i)} \right)$
8: $\quad\quad$ **else**
9: $\quad\quad\quad$ $T^{fin}_{ev(i)} = \left(T^{arr}_{ev(i)} + T^{cha}_{ev(i)} \right)$
10: $\quad\quad$ **end if**
11: $\quad\quad$ replace ATCLIST.GET(0) with $T^{fin}_{ev(i)}$
12: $\quad$ **end if**
13: **end for**
14: **if** (ATCLIST.GET(0) < TS) **then**
15: $\quad$ **return** TS
16: **else**
17: $\quad$ **return** ATCLIST.GET(0)
18: **end if**

---

1) Algorithm 3-EETAC Computation With EVs' Reservations: With the knowledge about those EVs (in REVLIST)

made reservations before a time slot TS, Algorithm 3 details the computation of EETAC at such TS. Note that these certain EVs made reservations are from REVLIST, as already processed by Algorithm 2.

For a given CS, the available time for charging per charging slot as included in ATCLIST, is generated via Algorithm 1 and sorted based on the ascending order. Here, the earliest available time for charging as given by ATCLIST.GET(0), is at the head of ATCLIST.

Starting from line 3, for each EV$_i$ in the REVLIST, its arrival time $T^{arr}_{ev(i)}$ will be involved for following calculation:

- If $T^{arr}_{ev(i)}$ is earlier than earliest available time for charging, the charging finish time $T^{fin}_{ev(i)}$ is given by $\left(\text{ATCLIST.GET}(0) + T^{cha}_{ev(i)} \right)$, presented between lines 6 and 7. This is because that the charging of EV$_i$ needs to wait for a period of time, where ATCLIST.GET(0) is the charging start time and $T^{cha}_{ev(i)}$ is the charging time of EV$_i$.

- Alternatively, $T^{fin}_{ev(i)}$ is given by $\left(T^{arr}_{ev(i)} + T^{cha}_{ev(i)} \right)$ as presented at line 9. This is because a charging slot has already been free upon the arrival of EV$_i$, as the charging start time is $T^{arr}_{ev(i)}$.

By replacing ATCLIST.GET(0) with $T^{fin}_{ev(i)}$ in each loop, the available time for charging per charging slot in ATCLIST will be dynamically updated, until all EVs in REVLIST have been processed. On one hand, the condition (ATCLIST.GET(0) < TS) at line 14 implies that the CS will be free for charging at TS, thus the input TS is given as the EETAC at this time slot. On the other hand, the ATCLIST.GET(0) is returned.

2) Algorithm 4-EETAC Computation Without EVs' Reservations: As presented at line 2 in Algorithm 4, the current time in network T_{cur} is estimated as the EETAC. This happens if none of EVs is under charging, as the condition given by $(N_C = 0)$. Besides, T_{cur} is estimated as the EETAC, if all charging slots of a CS have not been fully occupied, as given by $(N_C < \delta)$.

For those EVs locally parking at the CS, we consider two types of queues respectively. Those EVs which are under charging are characterized in the queue of N_C, while those still waiting for charging are characterized in the queue of N_W. In general, Algorithm 4 starts from processing each EV$_i$ in the queue of N_C, where its time duration $\left(\frac{E^{max}_{ev(i)} - E^{cur}_{ev(i)}}{\beta} \right)$ to be fully recharged will be aggregated with T_{cur}. This aggregated value indicating the charging finish time of EV$_i$, is inserted into the ATCLIST.

Then, Algorithm 4 will return the EETAC depending on one of the following conditions:

- **Condition-1:** Either if the number of EVs waiting for charging is 0, as the condition stated at line 7.

- **Condition-2:** Or a loop operation for each EV$_j$ waiting for charging has been processed, as stated between lines 16 and 20.

Process for Condition-1: The minimum charging time of those EVs under charging (in the queue of N_C), denoted as T^{cha}_{min} is calculated via Algorithm 5. Followed by line 8 in

---

Algorithm 4 EETAC–Computation(TS)

1: **if** $((N_C = 0) \, || \, (N_C < \delta))$ **then**
2:    **return** T_{cur}
3: **end if**
4: **for** $(i = 1; \; i \le N_C; \; i + +)$ **do**
5:    ATCLIST.ADD $\left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta} + T_{cur} \right)$
6: **end for**
7: **if** $(N_W = 0)$ **then**
8:    define $T_{min}^{fin} = \left(T_{min}^{cha} + T_{cur} \right)$
9:    **if** $\left(T_{min}^{fin} < \text{TS} \right)$ **then**
10:       **return** TS
11:    **else**
12:       **return** T_{min}^{fin}
13:    **end if**
14: **end if**
15: sort the queue of N_W according to FCFS
16: **for** $(j = 1; \; j \le N_W; \; j + +)$ **do**
17:    sort ATCLIST with ascending order
18:    $T_{ev(j)}^{fin} = \left(\text{ATCLIST.GET(0)} + \frac{E_{ev(j)}^{max} - E_{ev(j)}^{cur}}{\beta} \right)$
19:    replace ATCLIST.GET(0) with $T_{ev(j)}^{fin}$
20: **end for**
21: **if** (ATCLIST.GET(0) < TS) **then**
22:    **return** TS
23: **else**
24:    **return** ATCLIST.GET(0)
25: **end if**

Algorithm 5 Calculate the T_{min}^{cha}

1: **if** $(N_C < \vartheta)$ **then**
2:    **return** $T_{min}^{cha} = 0$
3: **end if**
4: **for** $(i = 1; i \le N_C; i + +)$ **do**
5:    **if** $\left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta} < T_{min}^{cha} \right)$ **then**
6:       $T_{min}^{cha} = \left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta} \right)$
7:    **end if**
8: **end for**
9: **return** T_{min}^{cha}

Algorithm 4, the minimum charging finish time of a charging slot T_{min}^{fin} is calculated by $\left(T_{min}^{cha} + T_{cur} \right)$. Further to this, as presented from line 9, the EETAC is returned as T_{cur}, if T_{min}^{fin} is earlier than the input time slot TS. This is due to that a charging slot has already been free at TS time slot. Otherwise, T_{min}^{fin} itself is returned at line 12.

Process for Condition-2: The loop operation starts from sorting the queue of N_W based on the FCFS charging scheduling order. Meanwhile, the ATCLIST about when the charging of those EVs (in the queue of N_C) will be finished, is initialized with an ascending order. Normally, the charging finish time $T_{ev(j)}^{fin}$ of each EV_j (in the queue of N_W) will be replaced with ATCLIST.GET(0). Recall that the earliest available time is at the head of ATCLIST, as denoted by ATCLIST.GET(0). Then at line 18, $T_{ev(j)}^{fin}$ is a sum of the time to start charging ATCLIST.GET(0) and battery charging time $\left(\frac{E_{ev(j)}^{max} - E_{ev(j)}^{cur}}{\beta} \right)$. The ATCLIST will be sorted with ascending order at each loop, such that the earliest time for charging obtained by ATCLIST.GET(0), is used for computation in next loop. The above loop operation ends when all EV_j have been processed, and then the EETAC is returned following

the conditions at lines 21 and 23, similar to the discussion in Algorithm 3.

E. CS-Selection Decision Making

Algorithm 6 CS-Selection Decision Making

1: **for** $(i = 1; \; i \le (N_E - 1); \; i + +)$ **do**
2:    **if** $\left(\text{TS}_i \le T_{ev(dec)}^{arr} \right)$ && $\left(\text{TS}_{i+1} > T_{ev(dec)}^{arr} \right)$ **then**
3:       **return** $\left(\text{EETAC}_{\text{TS}_{(i)}} + \frac{T_{ev(dec)}^{arr} \times \left(\text{EETAC}_{\text{TS}_{(i+1)}} - \text{EETAC}_{\text{TS}_{(i)}} \right)}{\text{TS}_{(i+1)}} \right)$
4:    **end if**
5: **end for**
6: **if** $\left(\text{TS}_1 > T_{ev(dec)}^{arr} \right)$ **then**
7:    **return** $\text{EETAC}_{\text{TS}_{(1)}}$
8: **else if** $\left(\text{TS}_{N_E} \le T_{ev(dec)}^{arr} \right)$ **then**
9:    **return** $\text{EETAC}_{\text{TS}_{(N_E)}}$
10: **end if**

We denote the EV needs to make CS-selection decision, as EV_{dec}. Here, two bounding time slots can be obtained via the condition at line 2 of Algorithm 6, such that the arrival time of EV_{dec}, denoted as $T_{ev(dec)}^{arr}$ is between these two time slots TS_i and TS_{i+1}. In this case, we obtain $\left(\text{EETAC}_{\text{TS}_{(i)}} + \frac{T_{ev(dec)}^{arr} \times \left(\text{EETAC}_{\text{TS}_{(i+1)}} - \text{EETAC}_{\text{TS}_{(i)}} \right)}{\text{TS}_{(i+1)}} \right)$ at line 3, considering a ratio between $T_{ev(dec)}^{arr}$ and TS_{i+1}. From this calculation, we aim to capture the EETAC of the $EV_{(dec)}$, upon its arrival time between TS_i and TS_{i+1}.

There are also two cases if $T_{ev(dec)}^{arr}$ is out of the bound of the estimation periods:

- Due to that $T_{ev(dec)}^{arr}$ is earlier than the earliest estimation time slot (in the queue of N_E), denoted as TS_1, the EETAC upon the arrival of EV_{dec} is given by $\text{EETAC}_{\text{TS}_{(1)}}$ at line 7.
- Besides, due to that $T_{ev(dec)}^{arr}$ is later than the latest time slot (in the queue of N_E) denoted as TS_{N_E}, the EETAC in this case is given by $\text{EETAC}_{\text{TS}_{(N_E)}}$ at line 9.

By recursing Algorithm 6 in relation to each CS, the one with the minimum value of EETAC is then selected by EV_{dec} to travel for charging purpose.

F. EVs' Reservations Aggregation

Once a CS-selection decision is made, the motivation for each bus to aggregate EVs' reservations related to an explicit CS, is to reduce the communication cost (in terms of how many times the connection is established between a bus and the explicit CS). In detail, given the certain CS publication frequency Δ and its previous publication time stamp T_{pre}, the aggregated EVs' reservations will be published to that given CS before $(\Delta + T_{pre})$.

In Section III, we have denoted N_{ev} as the total number of EVs, and N_{bus} as the number of buses. Here, we have the following discussion on the communication efficiency of aggregating EVs' reservations, as compared to the cases applying either cellular network communication or without aggregation.

Cellular Network Communication (CNC): The EVs' reservations are sent to their selected CS through CNC, which will not experience delay due to ubiquitous communication range. Here, the communication cost $Cost_{CNC}$ is denoted as:

$$(Cost_{CNC} \geq O(N_{ev})) \tag{5}$$

This is because that the number of demands to generate reservations is directly related to that of EVs. Here, the charging reservation is only published, upon a CS-selection has been made by EV (meaning the EV needs charging). Therefore, given that the communication cost of CNC is $O(N_{ev})$, we make a simple assumption that each EV needs to charge more than once. However, the communication cost still follows $O(N_{ev})$ even if not all EVs need charging more than once.

Bus Relay (BR): The EVs' reservations are sent to their selected CS through opportunistically encountered buses. Referring to Fig.9, the delay is only from the time to encounter a bus, because the communication from the bus to CS is still through CNC. Here, the communication cost $Cost_{BR}$ is denoted as:

$$(Cost_{BR} \geq O(P_{(ac1)} \times N_{ev})) \tag{6}$$

where $P_{(ac1)}$ is the possibility for an EV to encounter at least one of buses.

Bus Relay&Aggregation (BRA): In this case, each bus will further aggregate its received EVs' reservations, which is related to the CS selected by these EVs making reservations. before the deadline of CS publication at next time stamp ($\Delta + T_{pre}$). The cost $Cost_{BRA}$ is then given by:

$$\left(Cost_{BRA} \geq O\left(\frac{N_{bus}}{\Delta} \right) \right) \tag{7}$$

Communication Efficiency of BRA: Based on the above, we obtain:

$$(Cost_{CNC} \geq Cost_{BR}) \tag{8}$$

To achieve $(Cost_{BR} > Cost_{BRA})$, we thereby need:

$$\left(P_{(ac1)} \times N_{ev} > \frac{N_{bus}}{\Delta} \right) \tag{9}$$

Excluding the mobility factor $P_{(ac1)}$, the communication efficiency of aggregation is reflected by:

- An increased number of EVs.
- A decreased number of buses.
- A decreased CS publication frequency.

G. Performance Evaluation

The performance is based on the same scenario detailed in Section III. Here, we set ($N_E = 10$) for computation purpose. Apart from the charging performance in terms of "**Average Waiting Time**" and "**Number of Charged EVs**" defined previously, we further bring another metric called "**Communication Cost**" indicating total number of connections established at all CSs.

1) Influence of CS Publication Frequency and Charging Slots: In Fig.11(a) and Fig.11(b), we observe that the Advanced Pull Mode outperforms Pull Mode, in terms of the average waiting time and number of charged EVs. Particularly, both schemes achieve a better performance in case

of a frequent 360s CS publication, compared to that given 3600s publication frequency. This is because that a frequent information publication reduces the data error at the EV side to make CS-selection decision, where the charging reservations at CSs as well as their ATC are received with a more recent value. Compared to the original Pull Mode by only using ATC, bringing EVs' reservations improves performance by considering EVs' future movement. Besides, increasing the number of charging slots improves performance, since the parallel charging process enables more EVs to be charged simultaneously.

In Fig.11(c), only the number of connections established to CSs is evaluated, because TABLE X already shows a close charging performance between CNC and BR. We observe that the communication cost is remarkably reduced by aggregating EVs' charging reservations at the bus side, shown as the BRA case. The gain is even improved with an infrequent CS publication, which follows our previous discussion. It is highlighted that both the performance given CNC and BR cases are not affected by CS publication frequency, as they are independent of periodical information publication. Here, the ubiquitous communication (referred to CNC case) inherently brings a higher cost than opportunistic communication (referred to BR case). Of course, applying more charging slots will have to bring much cost, since the number of charging demands is increased.

TABLE X
ADDITIONAL RESULT 1: COMPARISON BETWEEN CNC AND BR

Schemes	Average Waiting Time	Number of Charged EVs
Default (CNC)	1100s ($\pm$7)	1056 ($\pm$5)
Default (BR)	1121s ($\pm$11)	1050 ($\pm$7)
3600s Publication Frequency (CNC)	3281s ($\pm$34)	878 ($\pm$2)
3600s Publication Frequency (BR)	3318s ($\pm$43)	874 ($\pm$4)
7 Charging Slots (CNC)	721s ($\pm$5)	1118 ($\pm$12)
7 Charging Slots (BR)	735s ($\pm$3)	1114 ($\pm$4)

TABLE XI
ADDITIONAL RESULT 2: COMPARISON BETWEEN CNC AND BR

Schemes	Average Waiting Time	Number of Charged EVs
Default (CNC)	1100s ($\pm$7)	1056 ($\pm$5)
Default (BR)	1121s ($\pm$11)	1050 ($\pm$7)
100m Transmission Range (CNC)	1152s ($\pm$40)	1046 ($\pm$4)
100m Transmission Range (BR)	1168s ($\pm$52)	1033 ($\pm$5)
1 Bus (CNC)	1220s ($\pm$42)	1045 ($\pm$5)
1 Bus (BR)	1247s ($\pm$71)	1042 ($\pm$8)

2) Influence of Bus Density and Transmission Range: By increasing the number of buses to relay information, both the average waiting time and number of charged EVs are improved in Fig.12(a) and Fig.12(b), thanks to more chances for EVs to access information from buses. Such observation applies to both the Advanced Pull Mode and original Pull Mode, where the former still outperforms latter. Particularly, the performance is almost the same regardless of transmission range, when the number of buses on each route reaches 15. This reveals a practical concern that, applying either a small number of buses with long transmission range, or more
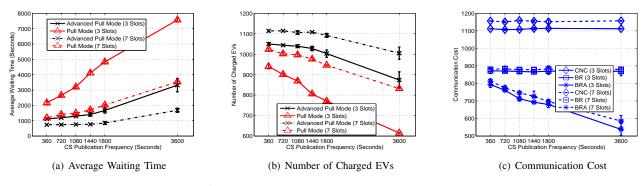
(a) Average Waiting Time

(b) Number of Charged EVs

(c) Communication Cost

Fig. 11. Influence of CS Publication Frequency & Number of Charging Slots

(a) Average Waiting Time

(b) Number of Charged EVs
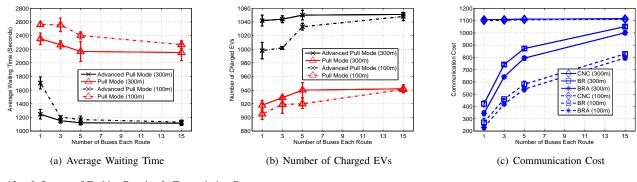
(c) Communication Cost

Fig. 12. Influence of Entities Density & Transmission Range

buses with short range communication can achieve a close performance.

In Fig.12(c), varying transmission range or number of buses does not affect the performance in case of CNC, whereas the BR case benefits from this. Here, aggregating EVs' reservations still shows its efficiency, based on the close charging performance between CNC and BR cases in TABLE XI.
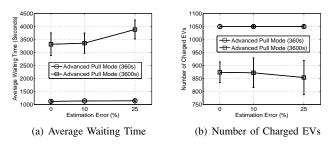

(a) Average Waiting Time

(b) Number of Charged EVs

Fig. 13. Influence of Estimation Error on EV Arrival Time

H. Influence of Estimation Error on EV Arrival Time

In Fig.13(a) and Fig.13(b), we set estimation error for EV arrival time, which has influence on the CS-selection intelligence of Advanced Pull Mode. Inevitably, a high estimation error (25%) remarkably degrades charging performance, given 3600s CS publication frequency. In comparison, that is insignificant in case of 360s CS publication frequency, thanks to the frequent publication inherently bringing low information error. Here, we have reflected the impact of inaccurate EVs arrival, e.g., due to traffic congestion (involved in charging reservation) on the actual charging performance. Note that previous works on charging scheduling (when EVs are parking at homes/CSs) [29] have addressed the uncertain EV arrival, our future work will tackle how to dynamically manage on-the-move EV charging given such mobility uncertainty in a distributed manner, rather than [30]. This requires substantial efforts to analyze the EVs traffic, and a well provisioned communication framework to enable timely and efficient information update (charging reservation used for computation of EETAC).

I. Comparison Against Other Reservation Based Charging Management Scheme

We further compare our proposal with previous work [12], which also takes the advantage of EVs' charging reservations for making CS-selection decision. Substantial difference between our proposal with previous work has been highlighted in Section II. Here, we directly integrated that charging management scheme on top of our Advanced Pull Mode communication for fair comparison. Results in Fig.14(a) and Fig.14(b) demonstrates the intelligence of our proposal over that literature work, particularly both of these two schemes utilize EVs' reservations.

V. CONCLUSION

In this article, we proposed an efficient communication framework for on-the-move EV charging application, based on the P/S mechanism and public buses to disseminate the condition information of CSs. We analyzed the possibility for EVs to access this information from buses, and proposed a CS-selection decision making included for EV charging

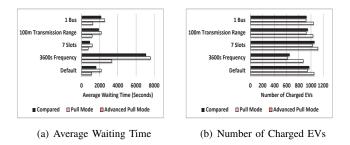(a) Average Waiting Time   (b) Number of Charged EVs

Fig. 14.   Comparison With Literature Work [12]

management. Evaluation results showed that how frequent CSs publish their condition information drives the charging performance in terms of charging waiting time and number of charged EVs. Observation shows the flexibility and mobility of buses brings an improved charging performance, compared to the case with deployed RSUs. Further effort on intelligent CS publication controlling via the knowledge of EVs' reservations, shows an improved charging performance. Meanwhile, the benefit of aggregating reservations is reflected by the reduced communication cost.

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